Active Fault-tolerant Control of Unmanned Underwater Vehicles

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Abstract

In this paper, a hierarchical systematic design methodology of active fault tolerant control system is developed to accommodate partial actuator and/or sensor faults of Unmanned Underwater Vehicles (UUVs). An integrated sensitive Fault Detection and Diagnosis (FDD) mechanism is developed with acceptable time period and a computation load reduction for large number of actuators and sensors in the presence of system disturbances and random noise. An optimized robust reconfigurable controller design is presented based on singular value decomposition (SVD) principle and eigenstructure assignment technique. The effectiveness of the proposed scheme has justified by simulation result on the decoupled steering subsystem of the Naval Postgraduate School (NPS) Unmanned Underwater Vehicles (UUVs).

Keywords

Unmanned Underwater Vehicles (UUVs); Model-based Fault Detection and Diagnosis (FDD); Fault-Tolerant Control System (FTCS); Controller reconfiguration; Singular Value Decomposition (SVD) Principle; Eigenstructure Assignment Technique (EA)

Introduction

Nowadays, control systems are everywhere in our life but unfortunately, they can't work perfectly at all time. The need to design controllers that guarantee both system stability and acceptable performance upon the occurrence of faults has been a hot topic of research. Faults being dynamic in nature, the fault-tolerant control system (FTCS) should be capable of accommodating them quickly, especially for complex systems e.g. unmanned underwater vehicles, aircraft/helicopter, spacecraft, hazardous chemical plants, and control of nuclear reactors. The fault tolerant control system (FTCS) is defined as a control system that possesses the ability to accommodate system component failures automatically (Y. M. Zhang, 2008) (J. Jiang, 2005). A system is Fault Tolerant (FT) able to recover its original task after a fault occures, with the same or degraded acceptable performances. Fault tolerant control (FTC) approaches are categorized into two types (Y. M. Zhang, 2008): passive and active approaches. Passive FTC (PFTCS) can tolerate a class of predefined set of faults considered at the controller design stage and needs neither fault detection and diagnosis (FDD) schemes nor controller reconfiguration. Active FTCS (AFTCS) on the other hand, employs Fault Detection and Identification (FDI) scheme that monitors system performance to detect and isolate faults (S., Katipamula, PartI, 2005) (S., (Katipamula, PartII, 2005). Accordingly, the control law is reconfigured on-line. Figure 1 demonstrates the typical components of AFTCS that implies a sensitive FDD scheme to provide precise and the most up-to-date information about the system as soon as possible after the fault occurrence and controller reconfiguration mechanism that organizes the on-line reconfigurable controller to recover the pre-fault system performance.

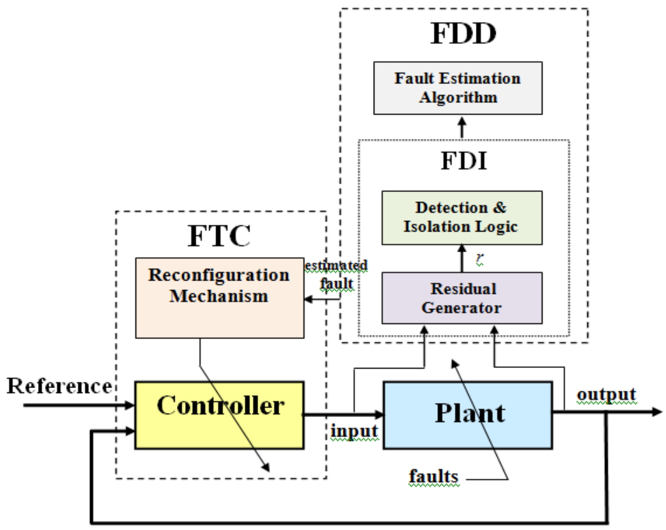


FIG. 1 ACTIVE FAULT TOLERANT CONTROL SYSTEM (FTCS) COMPONENTS

Since Unmanned Underwater Vehicles (UUVs) are widely used in commercial, scientific, and military

missions for various purposes, it is necessary to embed FTC paradigms into UUVs to increase the reliability of the vehicles and enable them to execute and finalize complex missions (A. Alessandri, , M. Caccia, G. Veruggio, 1997) (A. Alessandri, M. Caccia, and G. Veruggio, 1999) (M. Caccia, & G. Veruggio, 2000) (Podder T.K. & Sarkar N., 2001) (A. Healey, and D. Lienard, 1993). Earlier investigations of literature employed parameter estimation and state-estimation methods for fault detection and diagnosis in UUVs. The state-estimation method monitors the system status based on an analytical model, whereas the parameter estimation method determines the system status based on system identification, where the residuals refer to plant parameters, rather than state variables. The parameter-estimation method does not require the analytical model in advance. This is especially helpful in those areas where analytical models are not easy to develop. In this paper, a systematic active fault tolerant control system (AFTCS) design that integrates fault detection, diagnosis and accommodation is developed. The design procedures imply: (1) an integrated design of a model-based fault detection and isolation (FDI) technique using a bank of constrained Kalman filters estimators, (2) an obvious fault estimation algorithm is derived that can estimate the effectiveness factor of a detected faulty sensor or actuator in the presence of the simulated system disturbance and measurement noise, and (3) a flexible approach to an on-line controller reconfiguration design for the post-fault system to compensate for detected failures leads to performance degradation or damages to the system. A reconfigurable state feedback controller with reference input is designed to recover the pre-fault system both transient and steady state performance based on eigenstructure assignment technique and singular value decomposition (SVD) principle. This paper is organized as follows: Section 2 provides system analysis. Section 3, fault detection and diagnosis. Section 4 shows the reconfigurable controller design. Section 5 presents simulation results for the steering subsystem of the Naval Postgraduate School (NPS) UUV with simulated actuator (rudder) failures. Finally, concluding remarks are made in section 6 followed by the list of references.

System Analysis

Unmanned Underwater Vehicle Kinematics

The kinematic relationships for the unmanned underwater vehicles (UUV) modeling discusses the motion in six degrees of freedom (DOF). Figure 2 shows the schematic diagram of UUV body's inertial coordinate axes definition and six motion components i.e. surge, sway, heave, roll, pitch and yaw. For marine vehicles, it is common to use the Society of Naval Architects and Marine Engineers (SNAME) notation summarized in Table 1 (SNAME, 1950).

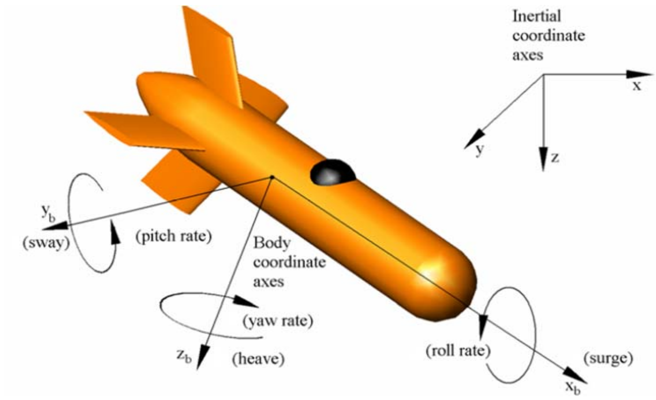


FIG. 2 THE SCHEMATIC DIAGRAM OF UUV BODY AND INERTIAL COORDINATE AXES DEFINITION

TABLE 1 SNAME NOTATION USED FOR MARINE VEHICLES

6 motion components	Forces and moments	Linear and angular velocities	Positions And Euler Angles
surge (motions in the x-direction)	X	u	x
sway (motions in the y-direction)	Y	v	y
heave (motions in the z-direction)	Z	ω	z
roll (rotation about the x-axis)	K	p	φ
pitch (rotation about the y-axis)	M	q	θ
yaw (rotation about the z-axis)	N	r	ψ

There are two coordinate reference frames denoted as the body-fixed reference frame B $(X_o\ Y_o\ Z_o)$, and the inertia-fixed frame I $(X\ Y\ Z)$ as indicated in figure A.1. The motion of the body-fixed frame is described relative to the inertial reference frame and the origin O of frame B is usually chosen at the center of gravity (CG) when the CG is in the principal plane of symmetry. The body-fixed axes X_o, Y_o, Z_o coincide with the principal axes of inertia with the longitudinal axis X_o pointing from aft to fore, the transverse axis Y_o to

starboard, and the normal axis Z_o from top to bottom. The position and orientation of the vehicle ($x, y, z, \varphi, \theta, \psi$) are described relative to frame *I*, while expressing the linear and angular velocities of the vehicle ($u, \upsilon, \omega, p, q, r$) in the body-fixed coordinate system.

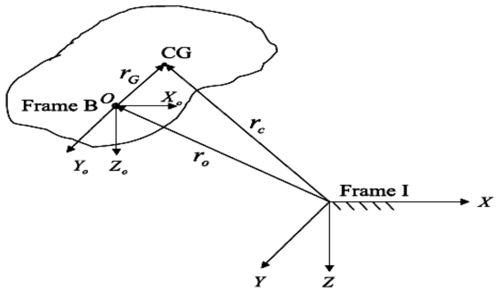


FIG. 3 BODY-REFERENCE FRAMES FOR UNDERWATER VEHICLE

The coordinates are grouped into two vectors as:

$$\eta = [\eta_1^T \ \ \eta_2^T]^T = [x \ \ y \ \ z \ \ \phi \ \ \theta \ \ \psi]^T \tag{1}$$

$$\nu = [\nu_1^T \ \ \nu_2^T]^T = [u \ \ \upsilon \ \ \omega \ \ p \ \ q \ \ r]^T \tag{2}$$

where η represents the vector of position and orientation of the vehicle in the inertial frame while ν represents the vector of linear and angular velocity of the vehicle in the body-fixed frame. The six degrees of freedom (DOF) equations that are used to describe the kinematic transformation between frame *I* and frame *B* are given as (T. I. Fossen, 1994) (T. I. Fossen, 2002):

$$\dot{\eta} = J(\eta)\nu \tag{3}$$

where $J(\eta)$ is a nonlinear transformation matrix and can be written as:

$$J(\eta) = \begin{bmatrix} J_1(\eta_1) & 0 \\ 0 & J_2(\eta_2) \end{bmatrix} \tag{4}$$

Unmanned Underwater Vehicle Dynamics

The 6-DOF nonlinear dynamic equations of motion are expressed in a compact form as (T. I. Fossen, 1994) (T. I. Fossen, 2002):

$$M\dot{\nu} + C(\nu)\nu + D(\nu)\nu + g(\eta) = \tau \tag{5}$$

where *M* is the inertia matrix of the vehicle, $C(\nu)$ is the matrix of Coriolis and centrifugal terms, $D(\nu)$ is the matrix of hydrodynamic damping terms, g is the vector of gravity and buoyant forces and τ is the control-input vector describing the forces and moments acting on the vehicle in the body-fixed frame. The body's inertia tensor corresponding to the body-fixed coordinate system X_o, Y_o and Z_o with origin *O* can be defined as:

$$I_o = \begin{bmatrix} I_x & -I_{xy} & -I_{xz} \\ -I_{yx} & I_y & -I_{yz} \\ -I_{zx} & -I_{zy} & I_z \end{bmatrix} \tag{6}$$

where I_x, I_y and I_z are the moments of inertia about the X_o, Y_o and Z_o axes, respectively. $I_{xy} = I_{yx}$, $I_{xz} = I_{zx}$, and $I_{yz} = I_{zy}$ are products of inertia. Fossen (T. I. Fossen, 1994) (T. I. Fossen, 2002) simplifies the equations of motion as:

$$m[\dot{u} - \upsilon r + \omega q - x_G(q^2 + r^2) + y_G(pq - \dot{r}) + z_G(pr - \dot{q})] = X \tag{7}$$

$$m[\dot{\upsilon} - \omega p + ur - y_G(r^2 + p^2) + z_G(qr - \dot{p}) + x_G(qp - \dot{r})] = Y \tag{8}$$

$$m[\dot{\omega} - u q + \upsilon p - z_G(p^2 + q^2) + x_G(rp - \dot{q}) + y_G(rq - \dot{p})] = Z \tag{9}$$

$$I_x\dot{p} + (I_z - I_y)qr + m[y_G(\dot{\omega} - u q + \upsilon p) - z_G(\dot{\upsilon} - \omega p + ur)] = K \tag{10}$$

$$I_y\dot{q} + (I_x - I_z)rp + m[z_G(\dot{u} - \upsilon r + \omega q) - x_G(\dot{\omega} - u q + \upsilon p)] = M \tag{11}$$

$$I_z\dot{r} + (I_y - I_x)pq + m[x_G(\dot{\upsilon} - \omega p + ur) - y_G(\dot{u} - \upsilon r + \omega q)] = N \tag{12}$$

where m is the mass of the body, x_G, y_G and z_G are the coordinate components of r_G. Due to the symmetric shape of UUVs, the center of gravity (CG) is usually taken as the origin *O* in such cases $r_G = [0, 0, 0]$. When the body axes coincide with the principal axes of inertia, it implies that the inertial tensor about the body's center of gravity is diagonal, i.e.

$$I_C = diag(I_{x_C}, \ I_{y_C}, \ I_{z_C}) \tag{13}$$

Subsequently, a simple representation will be yielded as (T. I. Fossen, 1994):

$$m(\dot{u} - \upsilon r + \omega q) = X \tag{14}$$

$$m(\dot{\upsilon} - \omega p + ur) = Y \tag{15}$$

$$m(\dot{\omega} - u q + \upsilon p) = Z \tag{16}$$

$$I_{x_C}\dot{p} + (I_{z_C} - I_{y_C})qr = K \tag{17}$$

$$I_{y_C}\dot{q} + (I_{x_C} - I_{z_C})rp = M \tag{18}$$

$$I_{z_C}\dot{r} + (I_{y_C} - I_{x_C})pq = N \tag{19}$$

Decoupled Subsystems of Unmanned Underwater Vehicle

Equation of motion introduced in the previous section is not practical for controller or observer design. Therefore, a control strategy for slender and symmetric vehicles is possible to separate the six-DOF equations of motion into non-interacting (or lightly interacting) subsystems, and design one controller for each

subsystem. For de-coupled control system design, we group together related equations of motion for separate functions of steering, diving, and forward speed (A. Healey, and D. Lienard, 1993) (T. I. Fossen, 1994) (T. I. Fossen, 2002) (B. Jalving, 1994). The three subsystems and their control and state variables are summarized in table A.2. Each subsystem has multiple states and a single control element. The steering subsystem controls heading errors, while the diving subsystem controls depth and pitch errors as well as the speed subsystem i.e. the surge subsystem controls the propeller dc motor. The steering subsystem dynamics is the most challenging one of the three almost decoupled sub-systems.

TABLE 2 CONTROL AND STATE VARIABLES OF UUV SUBSYSTEMS

Subsystem	State Variables	Control inputs
Speed Steering Diving	*u(t)* *υ(t), r(t), ψ(t)* *ω(t), q(t), θ(t), z(t)*	*n(t)* *δr(t)* *δs(t)*

Steering Subsystem of NPS UUV

Under the assumption of nearly constant speed $u \approx u_0$, the vehicle dynamics in sway and yaw can be simplified to:

$$m\dot{\upsilon} + m u_0\, r = Y \tag{20}$$

$$I_z\, \dot{r} = N \tag{21}$$

where

$$Y = Y_{\dot{\upsilon}}\, \dot{\upsilon} + Y_{\dot{r}}\, \dot{r} + Y_{\upsilon}\, \upsilon + Y_r\, r + Y_{\delta}\, \delta_r \tag{22}$$

$$N = N_{\dot{\upsilon}}\, \dot{\upsilon} + N_{\dot{r}}\, \dot{r} + N_{\upsilon}\, \upsilon + N_r\, r + N_{\delta}\, \delta_r \tag{23}$$

For small roll and pitch angles we can assume that $\dot{\psi} \approx r$. Based on the above assumptions, the linear equations of motion for the steering subsystem are expressed as (T. I. Fossen, 1994) (B. Jalving, 1994):

$$\begin{bmatrix} m\text{-}Y_{\dot{v}} & mx_G - Y_{\dot{r}} & 0 \\ mx_G\text{-}N_{\dot{v}} & I_z\text{-}N_{\dot{r}} & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} \dot{\upsilon} \\ \dot{r} \\ \dot{\psi} \end{bmatrix} = \begin{bmatrix} Y_v\, u_0 & Y_r - mu_0 & 0 \\ N_v\, u_0 & N_r - mx_G u_0 & 0 \\ 0 & 1 & 0 \end{bmatrix} \begin{bmatrix} \upsilon \\ r \\ \psi \end{bmatrix} + \begin{bmatrix} Y_\delta \\ N_\delta \\ 0 \end{bmatrix} \delta_r \tag{24}$$

From (24) we can write:

$$\begin{bmatrix} m\text{-}Y_{\dot{v}} & mx_G - Y_{\dot{r}} & 0 \\ mx_G\text{-}N_{\dot{v}} & I_z\text{-}N_{\dot{r}} & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} \dot{\upsilon} \\ \dot{r} \\ \dot{\psi} \end{bmatrix} = \begin{bmatrix} Y_v\, u_0 & (Y_r - m)u_0 & 0 \\ N_v\, u_0 & (N_r - mx_G)u_0 & 0 \\ 0 & 1 & 0 \end{bmatrix} \begin{bmatrix} \upsilon \\ r \\ \psi \end{bmatrix} + 0.5u_0^2 Y_\delta \begin{bmatrix} 1 & 1 \\ 0.283\text{L} & \text{-}0.377\text{L} \\ 0 & 0 \end{bmatrix} \begin{bmatrix} \delta_{rb} \\ \delta_{rs} \end{bmatrix} \tag{25}$$

Naval Postgraduate School's work determines the values of constants and coefficients in (25). Substituting and finally, rearranging it into a state-space form, we have:

$$\begin{bmatrix} \dot{\upsilon} \\ \dot{r} \\ \dot{\psi} \end{bmatrix} = \begin{bmatrix} -0.6383 & -1.4439 & 0 \\ 0.0591 & -0.4659 & 0 \\ 0 & 1 & 0 \end{bmatrix} \begin{bmatrix} \upsilon \\ r \\ \psi \end{bmatrix} + \begin{bmatrix} 0.1708 & \text{-}0.2650 \\ 0.1924 & 0.302 \\ 0 & 0 \end{bmatrix} \begin{bmatrix} \delta_{rb} \\ \delta_{rs} \end{bmatrix} \tag{26}$$

$$Y = \begin{bmatrix} 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} \upsilon \\ r \\ \psi \end{bmatrix} \tag{27}$$

The equivalent discrete linear state space model representation of the given system can be described as:

$$\mathrm{x}_{k+1} = \mathrm{A}\,\mathrm{x}_k + \mathrm{B}\,\mathrm{u}_k + \mathrm{w}_k \tag{28}$$

$$\mathrm{y}_k = \mathrm{C}\,\mathrm{x}_k + \mathrm{v}_k \tag{29}$$

where x_k is the state vector □R^{nx1}, *A* is the system matrix □R^{nxn}, *B* is the control matrix □R^{nxp}, u_k is the input control vector □R^{px1}, w_k is the system disturbances, y_k is the measured output □R^{qx1}, *C* is the output matrix □R^{qxn}, v_k is the measurement noise with zero mean. Using zero order hold with a sampling period *Ts* = 0.1s, the discrete model parameters will be given as:

$$A = \begin{bmatrix} 0.9378 & \text{-}0.1366 & 0 \\ 0.005592 & 0.9541 & 0 \\ 0.0002848 & 0.09769 & 1 \end{bmatrix} \quad B = \begin{bmatrix} 0.01521 & \text{-}0.02777 \\ 0.01884 & 0.02943 \\ 0.0009488 & 0.001484 \end{bmatrix}$$

and $C = \begin{bmatrix} 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix}$

Modeling Faults

The system model with actuator and/or sensor faults can be considered as (G. Liu, D. Wang, and Y. Li, 2004) (Y. M. Zhang and J. Jiang, 2002):

$$x_{k+1} = A\, x_k + B_f\, u_k + w_k \tag{30}$$

$$y_k = C_f\, x_k + v_k \tag{31}$$

where the actuator faults are modeled by:

$$B_f = B\,(I - \Gamma_a), \Gamma_a = \mathrm{diag}(\gamma_{a1}, \gamma_{a2}, ..., \gamma_{ap}) \tag{32}$$

where γ_{ai}, i=1, 2,…, p represent the control effectiveness factors that indicate the actuator multiplicative faults. If $\gamma_{ai} = 0$ then there is no fault. If $0 < \gamma_{ai} < 1$ then there is a partial fault or loss in control action. If $\gamma_{ai} = 1$ then there is a complete actuator failure. Similarly the sensor faults are modeled by:

$$C_f = (I - \Gamma_c)\, C, \Gamma_c = \mathrm{diag}(\gamma_{s1}, \gamma_{s2}, ..., \gamma_{sq}) \tag{33}$$

where γ_{si}, i=1, 2,…, q, represent the effectiveness factors that indicate the sensor faults. If $\gamma_{si} = 0$ then there is no fault. If $0<\gamma_{si}<1$ then there is a partial sensor fault. If $\gamma_{si} = 1$ then there is a complete sensor failure.

Fault Detection and Diagnosis

Fault Detection and Isolation

A model-based FDI technique is developed by using a set of constrained Kalman filters for fault detection and isolation (G. Liu, D. Wang, and Y. Li, 2004). Fault isolation for a set of components and/or a single component is achieved by generating structured residual signals sensitive to certain faults and insensitive to others by partitioning the input control matrix B to two input matrices B_{incl} and B_{excl} consequently the input control vector u_k is partitioned to u_{incl} and u_{excl} respectively for individual actuator fault isolation. Similarly, the output matrix C is partitioned to two matrices C_{incl} and C_{excl} and so the output vector y_k is partitioned to y_{incl} and y_{excl} respectively for individual sensor fault isolation. The system state space model of equations (28) and (29) becomes:

$$x_{k+1} = A\, x_k + B_{incl}\, u_{incl}(k) + B_{excl}\, u_{excl}(k) + w_k \tag{34}$$

$$y_k = \begin{bmatrix} y_{incl}(k) \\ y_{excl}(k) \end{bmatrix} = \begin{bmatrix} C_{incl} \\ C_{excl} \end{bmatrix} x_k + v_k \tag{35}$$

where B_{incl} and B_{excl} for the i^{th} actuator are given as:

$$B_{incl} = \begin{bmatrix} 0 & \cdots & 0 & b_{1i} & 0 & \cdots & 0 \\ 0 & \cdots & 0 & b_{2i} & 0 & \cdots & 0 \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ 0 & \cdots & 0 & b_{ni} & 0 & \cdots & 0 \end{bmatrix},$$

$$B_{excl} = \begin{bmatrix} b_{11} & \cdots & b_{1(i-1)} & 0 & b_{1(i-1)} & \cdots & b_{1p} \\ b_{21} & \cdots & b_{2(i-1)} & 0 & b_{2(i-1)} & \cdots & b_{2p} \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ b_{n1} & \cdots & b_{n(i-1)} & 0 & b_{n(i-1)} & \cdots & b_{np} \end{bmatrix}$$

Similarly C_{incl} and C_{excl} for the i^{th} sensor are given as:

$$C_{incl} = \begin{bmatrix} 0 & 0 & \cdots & 0 \\ \vdots & \vdots & \cdots & \vdots \\ 0 & 0 & \cdots & 0 \\ c_{i1} & c_{i2} & \cdots & c_{in} \\ 0 & 0 & \cdots & 0 \\ \vdots & \vdots & \cdots & \vdots \\ 0 & 0 & \cdots & 0 \end{bmatrix}, C_{excl} = \begin{bmatrix} c_{11} & c_{12} & \cdots & c_{1n} \\ \vdots & \vdots & \cdots & \vdots \\ c_{(i-1)1} & c_{(i-1)2} & \cdots & c_{(i-1)n} \\ 0 & 0 & \cdots & 0 \\ c_{(i+1)1} & c_{(i+1)2} & \cdots & c_{(i+1)n} \\ \vdots & \vdots & \cdots & \vdots \\ c_{q1} & c_{q2} & \cdots & c_{qn} \end{bmatrix}$$

The discrete Kalman filter algorithm equations fall into two groups: time update equations (prediction) and measurement update equations (correction) represented as:

$$\hat{x}_{k+1/k} = A\, \hat{x}_{k/k} + B\, u_k \tag{36}$$

$$\hat{x}_{k+1/k+1} = A\, \hat{x}_{k+1/k} + g\,[y_{k+1} - C\, \hat{x}_{k+1/k}] \tag{37}$$

by suitable selection of The innovation updating gain matrix g provide decayed response for estimation error e_k where:

$$e_k = x_k - \hat{x}_{k/k} \tag{38}$$

and

$$e_{k+1} = x_{k+1} - \hat{x}_{k+1/k+1} \tag{39}$$

from (28) and (37) we can write:

$$e_{k+1} = (I - g\, C)\, A\, e_k + (I - g\, C)\, w_k - g\, v_k \tag{40}$$

squaring both sides and taking stochastic mean of (40) gives:

$$\begin{aligned} \Sigma_{ee}(k+1) = (I - g\, C)\, A\, \Sigma_{ee}(k)\, A^T\, (I - g\, C)^T + \\ (I - g\, C)\, \Sigma_{ww}\, (I - g\, C)^T + g\, \Sigma_{vv}\, g^T \end{aligned} \tag{41}$$

where Σ_{ee} is the state estimation error covariance, Σ_{ww} is the process disturbance covariance, Σ_{vv} is the measurement noise covariance. The predictor-corrector equations for (34) and (35) can be written as:

$$\hat{x}_{k+1/k} = A\, \hat{x}_{k/k} + B_{incl}\, u_{incl}(k) \tag{42}$$

$$\hat{x}_{k+1/k+1} = A\, \hat{x}_{k+1/k} + g\,[y_{incl}(k+1) - C_{incl}\, \hat{x}_{k+1/k}] \tag{43}$$

The error covariance of (41) has become:

$$\Sigma_{ee}(k+1) = (I - g\,C_{incl})\,A\,\Sigma_{ee}(k)\,A^T\,(I - g\,C_{incl})^T + (I - g\,C_{incl})\,\Sigma_{ww}\,(I - g\,C_{incl})^T + g\,\Sigma_{vv}\,g^T \quad (44)$$

taking the 1st order variance of (44) and then solving for Σ_{ee} and g. Fault detection here is reliant on determining e_k that will be close to zero depending on available noise and system disturbances but after fault occurrence it will be considerably high. For each included set of actuators or sensors and for each included single actuator or sensor, a constraint Kalman filter estimator is designed (E. Larson, B. Parker, and B. Clark, 2002). Fault isolation has performed by detecting the faulty set, then isolating the faulty single individual component within the faulty detected set. The residual signals generated by the state estimators are affected by system disturbances and noise, so a suitable threshold value can be used for fault detection level depending on the real system.

Fault Estimation

After the fault has been detected and isolated in a set of component (or in a single component) the next step for fault diagnosis is to estimate the value of the post-fault system, sensor effectiveness factor in equation (33) and the control effectiveness factor in equation (32). For the fault-free system, the sensor measurement matrix will be affected after sensor fault from:

$$C = [c_1, \ldots, c_i, \ldots, c_q]^T \;,\;\; i = 1,2,..,q \quad (45)$$

to:

$$C_f = [c_1, \ldots, (1-\gamma_{si})c_i, \ldots, c_q]^T \;,\;\; i = 1,2,..,q \quad (46)$$

where γ_{si} represents the estimated effectiveness factor in case of a fault in the ith sensor. The discrete Kalman filter algorithm equations (36), (37) considering ith sensor faults will be:

$$\hat{x}_{k+1/k+1} = \hat{x}_{k+1/k} + g\,[C_f\,x_{k+1} + v_k - C\,\hat{x}_{k+1/k}] \quad (47)$$

Then we can have:

$$\hat{x}_{k+1/k+1} = (I - g\,C)\;\hat{x}_{k+1/k} + g\,C_f\,x_{k+1} + g\,v_k \quad (48)$$

using equations (28) and (36) we can write:

$$\hat{x}_{k+1/k+1} = -(I - g\,C)A(x_k - \hat{x}_{k/k}) + (I - g\,C)\,x_{k+1} - (I - g\,C)\,w_k + g\,C_f x_{k+1} + g\,v_k \quad (49)$$

and equation (40) will be:

$$e^f_{k+1} = -(I - g\,C)A\,e^f_k + g\,\Delta C\,x_{k+1} + (I - g\,C)\,w_k - g\,v_k \quad (50)$$

where $\Delta C = C - C_f = [0, \ldots, \gamma_{si} c_i, \ldots, 0]^T$

The error covariance of (44) can be written as:

$$\Sigma^f_{ee}(k+1) = (I - g\,C)\,A\,\Sigma^f_{ee}(k)\,A^T\,(I - g\,C)^T + g\,\Delta C\,\Sigma_{xx}\,\Delta C^T g^T + (I - g\,C)\,\Sigma_{ww}\,(I - g\,C)^T + g\,\Sigma_{vv}\,g^T \quad (51)$$

where Σ^f_{ee} is the state estimation error covariance considering ith sensor fault, and Σ_{xx} is given as:

$$\Sigma_{xx} = E\{x_{k+1}\,x^T_{k+1}\} \quad (52)$$

from (41) and (51) we have:

$$\Delta\Sigma = \Sigma^f_{ee} - \Sigma_{ee} = (I - g\,C)\,A\,\Delta\Sigma\,A^T\,(I - g\,C)^T + g\,\Delta C\,\Sigma_{xx}\,\Delta C^T g^T \quad (53)$$

Let $\Delta C = \gamma_{si}\,\beta_s$ (54)

and $M_s = g\,\Delta C\,\Sigma_{xx}\,\Delta C^T g^T$ (55)

then $M_s = \gamma^2_{si}(\,g\,\beta_s\,\Sigma_{xx}\,\beta^T_s g^T) = \gamma^2_{si}\Theta_s$ (56)

where $\Theta_s = g\,\beta_s\,\Sigma_{xx}\,\beta^T_s g^T$ (57)

The effectiveness factor can be estimated as a mean value by rearranging non-zero elements of M_s and the corresponding non-zero elements of Θ_s into arrays M_{sk} and Θ_{sk} respectively, so we can write:

$$\gamma_{si} = \frac{1}{Ns}\left(\sum_{k=1}^{Ns}\sqrt{\frac{M_{sk}}{\Theta_{sk}}}\right) \quad (58)$$

where Ns is the total number of non-zero elements in M_s (or Θ_s) and k= 1,2,…,Ns. Similarly, for the fault-free system, the input control matrix that given as:

$$B = [b_1, \ldots, b_i, \ldots, b_p]\,,\;\; i = 1,2,..,p \quad (59)$$

will be affected after actuator fault to:

$$B_f = [b_1, \ldots, (1-\gamma_{ai})b_i, \ldots, b_p],\;\; i = 1,2,..,p \quad (60)$$

where γ_{ai} represents the loss in control effectiveness factor of the ith actuator. The discrete Kalman filter algorithm equations considering actuator faults will be:

$$\hat{x}_{k+1/k+1} = A\,\hat{x}_{k/k} + B\,u_k + g\,C\,A\,e_k + g\,C\,\Delta B\,u_k + g\,C\,w_k + g\,v_k \quad (61)$$

with $\Delta B = B - B_f = [0, \ldots, \gamma_{ai} b_i, \ldots, 0]$, equation (39) will be:

$$e^f_{k+1} = (I - g\,C)\,A\,e_k + (I - g\,C)\,\Delta B\,u_k + (I - g\,C)\,w_k - g\,v_k \quad (62)$$

also error covariance of (62) can be written as:

$$\Sigma^f_{ee}(k+1) = (I - g\,C)\,A\,\Sigma^f_{ee}(k)\,A^T\,(I - g\,C)^T + (I - g\,C)\,\Delta B\,\Sigma_{uu}\,\Delta B^T\,(I - g\,C)^T + (I - g\,C)\,\Sigma_{ww}\,(I - g\,C)^T + g\,\Sigma_{vv}\,g^T \quad (63)$$

where Σ^f_{ee} is the state estimation error covariance considering ith actuator fault, and Σ_{uu} is expected

covariance of the control input. From (41) and (63) we have:

$$\Delta\Sigma = \Sigma_{ee}^{f} - \Sigma_{ee} = (I - g\,C)\,A\,\Delta\Sigma\,A^{T}\,(I - g\,C)^{T} + (I - g\,C)\,\Delta B\,\Sigma_{uu}\,\Delta B^{T}\,(I - g\,C)^{T} \tag{64}$$

Let $\Delta B = \gamma_{ai}\beta_a$ (65)

and $M_a = (I - g\,C)\,\Delta B\,\Sigma_{uu}\,\Delta B^{T}\,(I - g\,C)^{T}$ (66)

then

$$M_a = \gamma_{ai}^{2}((I - g\,C)\,\beta_a\,\Sigma_{uu}\,\beta_a^{T}\,(I - g\,C)^{T}) = \gamma_{ai}^{2}\Theta_a \tag{67}$$

where $\Theta_a = (I - g\,C)\,\beta_a\,\Sigma_{uu}\,\beta_a^{T}\,(I - g\,C)^{T}$ (68)

The effectiveness factor can be estimated as a mean value by rearranging non-zero elements of M_a and the corresponding non-zero elements of Θ_a into arrays M_{ak} and Θ_{ak} respectively, so we can write:

$$\gamma_{ai} = \frac{1}{Na}\left(\sum_{k=1}^{Na}\sqrt{\frac{M_{ak}}{\Theta_{ak}}}\right) \tag{69}$$

where Na is the total number of non-zero elements in M_a (or Θ_a) and k= 1,2,…,Na

Reconfigurable Controller Design

The activation of the reconfiguration process is constrained by the following condition (Y. M. Zhang and J. Jiang, 2002) (Y. M. Zhang and J. Jiang, 2001):

$$\xi_k^i = \left|\gamma_k^i - \gamma_{k-1}^i\right| < \delta^i,\ \forall\, i = 1,\dots,p \tag{70}$$

where δ^i is the threshold level involved as a design parameter and ξ^i_k represents the errors in the consecutive control effectiveness factor estimation. The reconfigurable fault tolerant control system design is required to recover the pre-fault system both transient and steady state performance based on the accurate FDD, taking into account the performance degradation in the occurrence of actuator faults (Y. M. Zhang and J. Jiang, 2003). The system representation in (28), (29) is assumed to be both controllable, observable and input as well as output matrices are of full rank, then the state feedback controller of the form:

$$u_k = -Kx_k + K_{forward}\,r_k \tag{71}$$

can be designed to find the gain matrix K $\in R^{pxq}$ using singular value decomposition (SVD) principle for predefined eigenvalues $\{s_j\ ;\ j = 1,2,\dots,m\}$ where r_k represents the reference input and $K_{forward}$ denotes the feedforward control gain to achieve steady-state tracking of the reference input (T. Didier, J. Cédric, Y. M. Zhang, 2008) i.e.

$$\lim_{k\to+\infty} y = r \tag{72}$$

By using a linear state transformation of the state vector x_k to the input-closed state space as:

$$x_k = T\,x_{kT} \tag{73}$$

The closed loop system model can be written as:

$$x_{(k+1)T} = (A_T - B_T\,K)\,x_{kT} + B_T\,K_{forward}\,r_k \tag{74}$$

where $T = \left[\,B \,\middle|\, \begin{matrix} I_p \\ 0_{n,n-p} \end{matrix}\right]$ and I_p is identity matrix $\in R^{pxp}$,

$A_T = T^{-1}\,A\,T,\ B_T = T^{-1}\,B$

The closed loop eigenvalues denoted by s_j and the j[th] right associated eigenvectors denoted by v_j represented as:

$$(A_T - B_T\,K)\,v_j = s_j v_j,\quad j = 1, 2,\dots, m \tag{75}$$

rearranging (75) we can write:

$$\left[\, s_j\,I - A_T \,\middle|\, \begin{matrix} I_p \\ 0_{n,n-p} \end{matrix} \right]\begin{bmatrix} v_j \\ Kv_j \end{bmatrix} = h_{Tj}\begin{bmatrix} v_j \\ Kv_j \end{bmatrix} = 0 \tag{76}$$

Applying singular value decomposition (SVD) principle to h_{Tj} gives:

$$h_{Tj} = L_{jn}\,\sigma_{jn}\,P_{jn}^{T} \tag{77}$$

where L_{jn} and P^T_{jn} are the left and right singular vectors respectively and σ_{jn} represents the set of singular values of h_{Tj} matrix. Through that principle, the achievable eigenvectors are located in the subspace with dimension determined by the number of inputs (rank (B)) and orientation determined by the matrices (A_T, B_T) and the desired eigenvalues s_j. As all column vectors $\{P_{jk}, k=p+1,\dots,n+p\}$ of the right singular vectors P_{jn} generated by using singular value decomposition (SVD) procedures satisfy the following condition:

$$h_{Tj}\,P_{jk} = 0 \tag{78}$$

from (76) we can write:

$$P_{jk} = \begin{bmatrix} Q_j \\ w_j \end{bmatrix} = \begin{bmatrix} v_j \\ K\,v_j \end{bmatrix} = \begin{bmatrix} Q_j \\ K\,Q_j \end{bmatrix} \tag{79}$$

Where $Q \in R^{nxn}$, $W \in R^{pxn}$, then using singular value decomposition (SVD) based solution for the desired eigenvalues to construct the gain matrix K we have:

$$W = K\,Q \tag{80}$$

and gain matrix K is given as:

$$K = W\,Q^{-1} \tag{81}$$

The reconfigurable control law for the post-fault system can be written as:

$$u_k = -K_f\,x_k + K_{forward}^{f}\,r_k \tag{82}$$

where K_f, $K^f_{forward}$ are the control gain matrices of the post-fault system. To achieve the same steady-state tracking of the reference input for the post-fault system (G. Liu, D. Wang, and Y. Li, 2004):

$$B K_{forward} = B_f \, K^f_{forward} \tag{83}$$

By the definition on another linear state transformation of the state vector x_k to the input-closed state space, the transformed system matrices are given as:

$T_f = \left[B_f \;\middle|\; \begin{matrix} I_p \\ 0_{n,n-p} \end{matrix} \right]$ and I_P is identity matrix $\in R^{pxp}$,

$$B_{fT} = T_f^{-1} \, B_f, \quad A_T = T_f^{-1} \, A \, T_f \tag{84}$$

The control reconfiguration using eigenstructure assignment is used here to guarantee the stability of the reconfigured system by recovering the system eigenvalues and to recover the pre-fault system performance to the maximum extent by placing the eigenvectors as close to those of the original system as possible (D. Krokavec, , 2005) (A. Esna Ashari, A. Khaki Sedigh, M. J. Yazdanpanah, 2005) i.e.

$$\lambda_i^f = \lambda(A_T - B_T K) = \lambda(A_T - B_{fT} K_f) = \lambda_i \, , i = 1,2,\dots, n \tag{85}$$

Both (75), (76) can be rewritten as:

$$(A_T - B_{fT} \, K_f) \, v_{fj} = s_j v_{fj}, \quad j = 1, 2,\dots, m \tag{86}$$

$$\left[s_j \, I - A_T \;\middle|\; \begin{matrix} I_p \\ 0_{n,n-p} \end{matrix} \right] \begin{bmatrix} v_{fj} \\ K_f v_{fj} \end{bmatrix} = h_{fTj} \begin{bmatrix} v_{fj} \\ K_f v_{fj} \end{bmatrix} = 0 \tag{87}$$

then applying singular value decomposition (SVD) principle procedures as previous steps to obtain the reconfigured gain matrix K_f.

Simulation Results

The following simulation results for the decoupled steering subsystem of NPS UUVs confirmed the effectiveness of the developed integrated AFTCS. The fault scenario is simulated as a partial actuator faults with effectiveness factor of 0.75 introduced at the sampling instants of 50 for the second actuator only. The proposed scheme uses six Kalman filter estimators, one for actuator group, one for sensor group, one for each actuator, and one for each sensor. Computer simulations are conducted using initial state vector x(0) =[0 0 0]^T. Due to the pure integration in the yaw channel of the steering subsystem, there is an eigenvalue of one for the equivalent discrete model. The desired eigenvalues of the steering subsystem are chosen as Sj= {0.9158, 0.9094, 1}. Applying the proposed controller design algorithm to the given faulty conditions provides the achievable K and Kf respectively as:

$$K = \begin{bmatrix} -0.1866 & -0.0953 & 0.0240 \\ -0.2971 & 0.1285 & 0.1473 \end{bmatrix}$$

$$K_f = \begin{bmatrix} -0.2136 & 0.0030 & 0.0827 \\ -0.1405 & 0.1555 & 0.3567 \end{bmatrix}$$

To achieve the same steady-state tracking of the reference input for the post-fault system, simulation results are performed using:

$$B \, K_{forward} = B_f \, K^f_{forward} = \begin{bmatrix} 0.0052 & -0.0095 \\ 0.0064 & 0.0101 \\ 0.0003 & 0.0005 \end{bmatrix}$$

In path tracking, we try to keep a constant heading angle 20 degree as a reference set-point for the heading angle of the steering subsystem. In simulating path tracking, the yaw rate of turn for the steering path is made to follow a reference input shown in figure 4. Figure 5 demonstrates the system output responses to fault-free system, the faulty system without controller reconfiguration case that declares the loss of control effect due to the simulated partial actuator fault, and finally, the post-fault system response with controller reconfiguration to show the effectiveness of the applied reconfiguration algorithm that recovers the pre-fault system both transient and steady state performances. The constrained Kalman Filter estimator for the actuators group has detected a fault at the sampling instants of 50 by tracking the actual faulty response of the system but the estimator for sensors group hasn't detected any faults and that is emphasized through the generated residual signals for actuators group and sensors group shown in figure 6 and figure 7 respectively. The residual signals of sensor group are close to zero depending on available measurement noise and system disturbances. To isolate the faulty actuator, the generated residual signals for the first actuator and the second actuator are declared in figure 8 and figure 9 respectively from which it is noted that the second actuator is responsible for the detected fault and that can be modeled as loss in control with effectiveness factor γ_{a2}. Through the introduced fault estimation technique, the last estimate of the loss of control effectiveness factor i.e. γa2 is 0.74995 that is close to the simulated applied partial actuator fault. Figure 10 shows the rudder control signals provided through the designed reconfigurable state feedback controller with reference input in which it can be seen

that the reconfigurable mechanism is activated after the fault has been detected, isolated and estimated using the integrated fault detection and diagnosis (FDD) scheme.

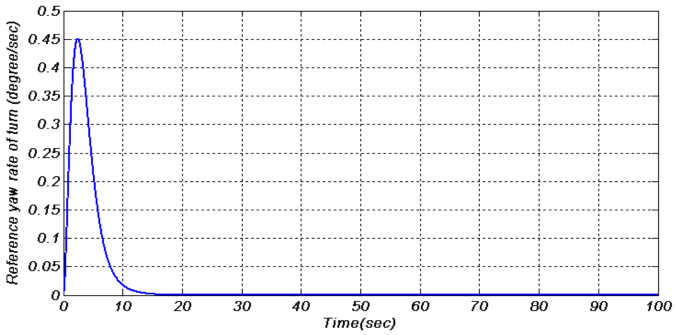
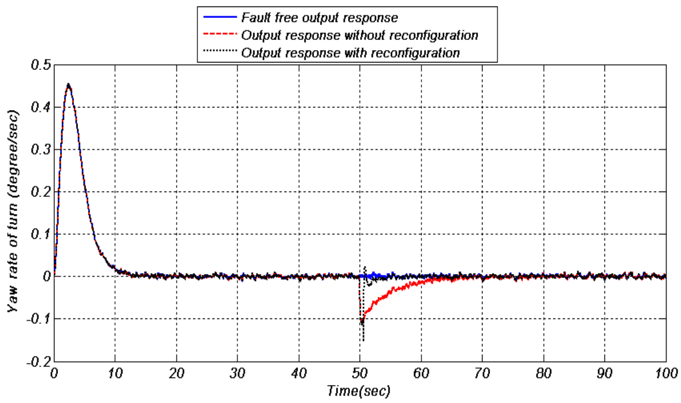
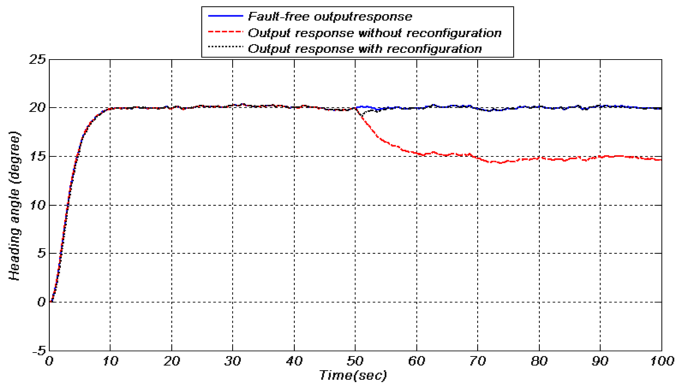


FIG. 4 REFERENCE INPUT FOR THE YAW RATE OF TURN FOR THE STEERING PATH

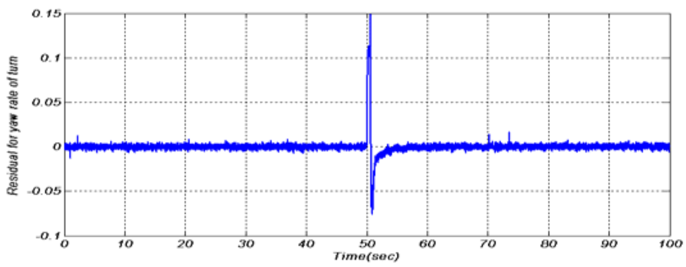


A. THE SYSTEM OUTPUT RESPONSE (Y1)

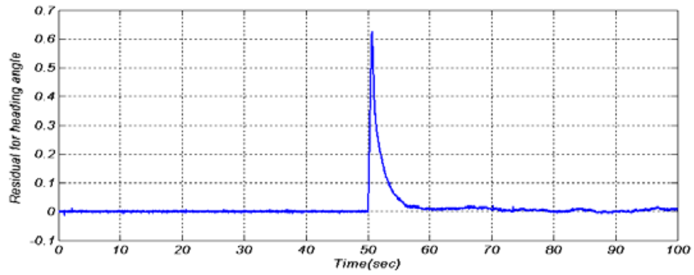


B. THE SYSTEM OUTPUT RESPONSE (Y2)

FIG. 5 THE SYSTEM OUTPUT RESPONSES OF FAULT-FREE AND FAULTY SYSTEM WITH AND WITHOUT RECONFIGURATION

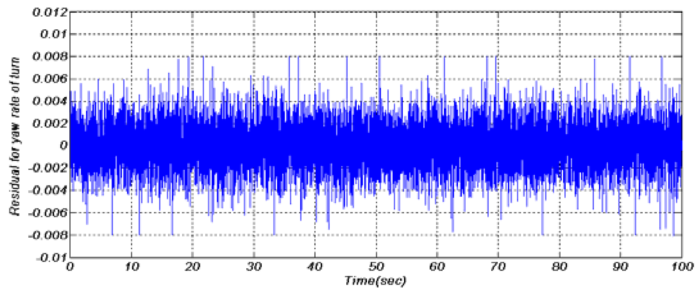


A. THE RESIDUAL FOR THE OUTPUT (Y1)

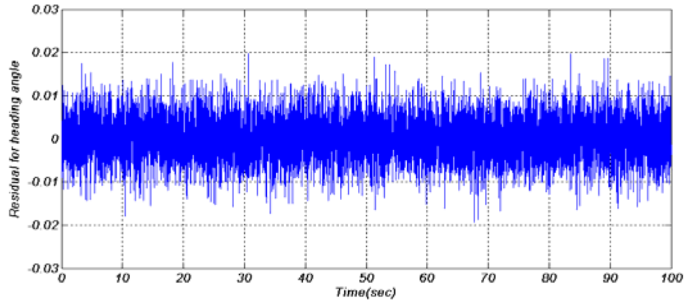


B. THE RESIDUAL FOR THE OUTPUT (Y2)

FIG. 6 THE RESIDUAL SIGNALS FOR ACTUATOR GROUP

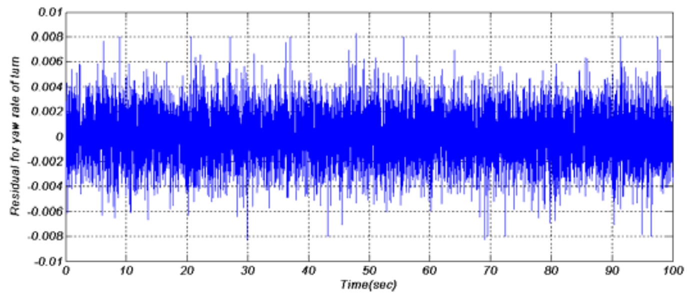


A. THE RESIDUAL FOR THE OUTPUT (Y1)

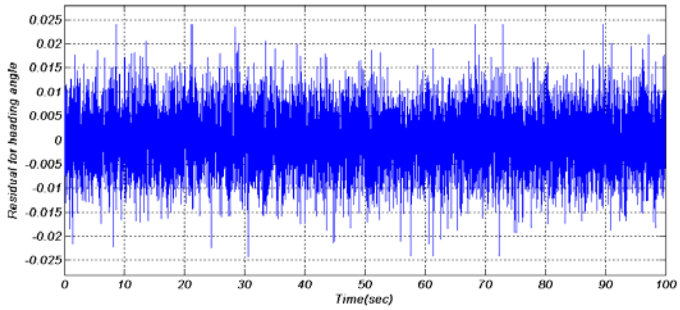


B. THE RESIDUAL FOR THE OUTPUT (Y2)

FIG. 7 THE RESIDUAL SIGNALS FOR SENSOR GROUP

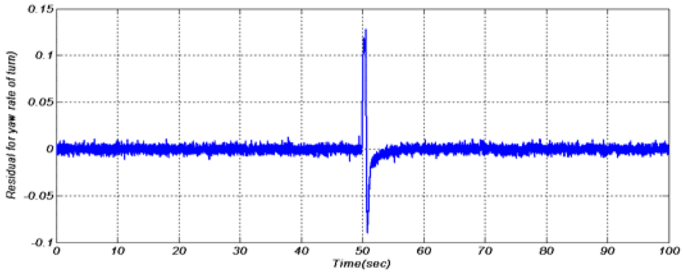


A. THE RESIDUAL FOR THE OUTPUT (Y1)

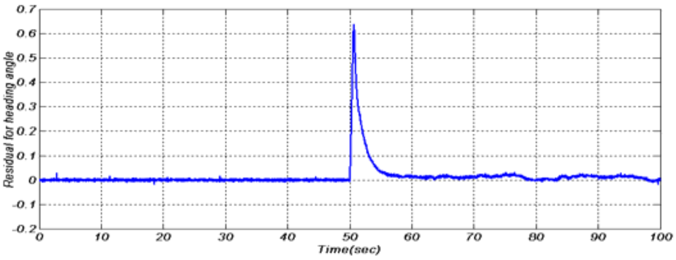


B. THE RESIDUAL FOR THE OUTPUT (Y2)

FIG. 8 THE RESIDUAL SIGNALS FOR THE FIRST ACTUATOR

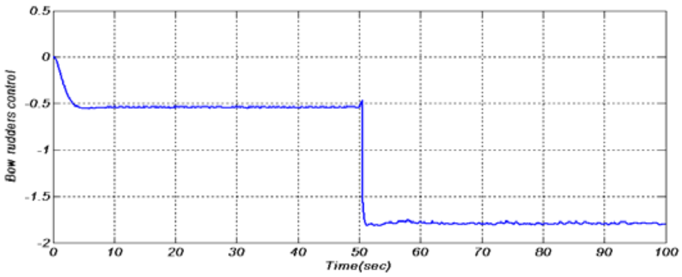


A. THE RESIDUAL FOR THE OUTPUT (Y1)

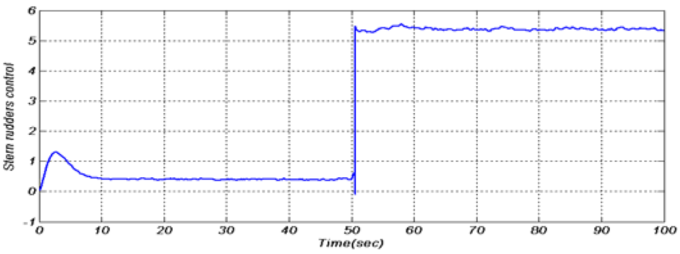


B. THE RESIDUAL FOR THE OUTPUT (Y2)

FIG. 9 THE RESIDUAL SIGNALS FOR THE SECOND ACTUATOR



A. BOW RUDDERS CONTROL SIGNAL



B. STERN RUDDERS CONTROL SIGNAL

FIG. 10 THE RUDDERS CONTROL SIGNALS

Conclusion

This paper presents an active fault-tolerant control system (AFTC) to accommodate partial actuator and/or sensor faults of Unmanned Underwater Vehicles (UUVs). The induced systematic approach provides sensitive and robust fault detection and diagnosis (FDD) system, a reconfigurable control design in a way that will preserve the stability of the system, combination of control reconfiguration and FDD system, a short and acceptable time period as both fault detection and isolation processes are achieved simultaneously as well as a computation load reduction for large number of actuators and sensors in the presence of system disturbances and random noise. The developed flexible approach based on Singular Value Decomposition (SVD) solution for eigenstructure assignment (EA) technique offers a powerful way to select robust reconfigurable control based on known state-space models of a dynamic system. The performances of the control reconfiguration approach are emphasized by simulation results of the fault-free case, the faulty case without reconfiguration and fault accommodation with controller reconfiguration.

REFERENCES

A. Alessandri, , M. Caccia, G. Veruggio, "Model-based fault detection for unmanned underwater vehicles". Safeprocess+97, Hull, UK , Vol. 2, pp. 615-620, 1997.

A. Alessandri, M. Caccia, and G. Veruggio, "Fault detection of actuator faults in unmanned underwater vehicles", IFAC Control Engineering Practice, vol. 7, no. 3, pp. 357-368, 1999.

A. Esna Ashari, A. Khaki Sedigh, M. J. Yazdanpanah, "Reconfigurable control system design using eigenstructure assignment: static,dynamic, and robust approaches," Int. J. of Control , 78, pp. 1005-1016, 2005.

A. Healey, and D. Lienard, "Multivariable Sliding Mode Control for Autonomous Diving and Steering of Unmanned Underwater Vehicles", IEEE Journal of Oceanic Engineering, Vol. 18, No. 3, pp. 327-339, 1993.

B. Jalving, "The NDRE-AUV Flight Control System", IEEE Journal of Oceanic Engineering, Vol. 19, No. 4, pp. 497-501, October 1994.

D. Krokavec, "Eigenstructure assignment in reconfigurable control system design," In Proceedings of the International Conference Cybernetics and Informatics 2005, Dolný Kubín, Slovak Republic, pp. 84-91, 2005.

E. Larson, B. Parker, and B. Clark, "Model-based sensor and actuator fault detection and isolation," In Proceedings of the American Control Conference, Anchorage, AK, pp. 4215—4219, 2002.

G. Liu, D. Wang, and Y. Li, "Active fault tolerant control with actuation reconfiguration," IEEE Trans. Aerospace and Electronic Systems, vol. 40, No. 3, pp. 1110-1117, 2004.

J. Jiang, "Fault-tolerant control systems—An introductory overview," Automatica SINCA, vol. 31, No.1, pp. 161–174, 2005.

M. Caccia, & G. Veruggio, “Guidance and control of a reconfigurable unmanned underwater vehicle”, Control Engineering Practice, 8(1), 21–37, 2000.

Podder T.K. & Sarkar N., Fault-Tolerant Control of an Autonomous Underwater Vehicle Under Thruster Redundancy, Journal of Robotics and Autonomous System, Vol. 34, pp. 39-52, 2001.

S., Katipamula, and M. R. Brambley, "Methods for Fault Detection, Diagnostics and Prognostics for Building Systems - A Review Part I", HVAC & R Research, Vol. 11, No. 1, pp. 3-25, 2005.

S., Katipamula, and M. R. Brambley, "Methods for Fault Detection, Diagnostics and Prognostics for Building Systems - A Review Part II", HVAC & R Research, Vol. 11, No. 2, pp. 169-187, 2005.

SNAME, "The society of naval architects and marine engineers", Nomenclature for treating the motion of a submerged body through a fluid, Technical and Research Bulletin, Vol. 1–5, 1950.

T. Didier, J. Cédric, Y. M. Zhang, “Actuator fault tolerant control design based on a reconfigurable reference input,” Int. J. Appl. Math. Comput. Sci., vol. 18, No. 4, pp. 553–560, 2008. DOI: 10.2478/v10006-008-0048-1

T. I. Fossen, "Guidance and Control of Ocean Vehicles", John Wiley and Sons Ltd. New York, 1994.

T. I. Fossen, "Marine Control Systems. Guidance, Navigation, and Control of Ships, Righs and Underwater Vehicles", Trondheim, Norway: Marine Cybernetics, 2002.

Y. M. Zhang and J. Jiang, “An active fault tolerant control system against partial actuator failures,” IEE Proceedings - Control Theory and Applications, vol. 149, No. 1, pp. 95-104, 2002.

Y. M. Zhang and J. Jiang, “Integrated Design of Reconfigurable Fault-Tolerant Control Systems,” Journal of Guidance, Control, and Dynamics, vol. 24, No.1, pp. 133-136, 2001.

Y. M. Zhang and J. Jiang, “Fault Tolerant Control System Design with Explicit Consideration of Performance Degradation,” IEEE Trans. on Aerospace and Electronic Systems, vol. 39, No.3, pp. 838-848, 2003.

Y. M. Zhang and J. Jiang, “Bibliographical review on reconfigurable fault- tolerant control systems,” Annual Reviews in Control. 32, pp. 229-252, 2008.